VELOCITY FLOW PROFILES OVER ROUGH BED IN OPEN CHANNELS

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الملخص

سرعة الدفق خلال الأسطح الخشنة للقنوات تعتبر ذات أهمية في مجال الهندسة الهيدروليكية حيث أن الغالب في قيعان الأنهار ومجاري المياه أنها من مواد رملية ولها تضاريس معقدة مثل التموجات في القاع. هذه الورقة تستقصي توزيع السرعة المتوسطة لدفق منتظم مضطرب على الأسطح الخشنة لقيعان القنوات المفتوحة وتقارنها ببعض النماذج النظرية المتاحة. إن نتائج التجارب قد أظهرت أن توزيع السرعة رأسيا من مستوى قاع القناة يمكن تقديره ببعض النماذج شريطة أن بعض المعاملات تقرب نسبيا وأن حالات الدفق يمكن تحديدها. إن الاعتقاد السائد بأن بعض هذه النماذج لها خاصية العمومية ويمكن تطبيقها على أغلب حالات الدفق ليست صحيحة كليا.

ABSTRACT

Velocity flows over rough beds are important in hydraulic engineering because almost all river beds are composed of sand grains and have complicated bed configuration like ripples. This study investigates mean velocity distribution of uniform turbulent flows over rough channel beds and compares these profiles with certain available models. Experiment results shows that velocity profiles can be estimated by certain theoretical models provided that some parameters are approximated and flow conditions are defined. The theory that some models are universal and can be used for all types of flows in the general sense can not stand.

Keywords: Open channel; Velocity profiles; Velocity distribution; Velocity components; Shear velocity; Rough beds.

INTRODUCTION

Many investigations have concentrated on the flow resistance and friction laws for the flow over fixed rough beds and over complicated bed configuration in fluvial open-channel flows. Although most of the smooth-bed flow velocity distributions can, however, be applied to flows over beds affected by wall roughness, knowledge of mean velocity over fixed sand-grain beds is, however, limited.

Two questions must be answered before turbulent flows over rough beds can be accurately described:

- What kind of parameter should be used to represent the size of roughness elements?
- Where should the theoretical wall be located?

Addressing question (1), Nikuradse used equivalent sand roughness k_s for his systematic experiments in pipe flows. For a rough bed composed of uniform sand grains attached densely to the wall, he found that the sand diameter itself can be used for k_s. For most roughnesses, the equivalent sand roughness k_s can be determined from the friction law derived from the log-law, for others one can determine the value of k_s from the mean velocity distribution in the region where it coincides with log-law of the wall region. However, these two methods for determining k_s do not necessarily give the same result. It may, for example, be difficult to determine the equivalent sand roughness k_s for an irregular surface.

The effects of roughness elements are usually classified in three categories, Nezu and Nakagawa (1993):

$$\left.\begin{array}{l}\text{a) Hydraulically smooth bed } (k_s^+ < 5)\\ \text{b) Incompletely rough bed} (5 \le k_s^+ \le 70)\\ \text{c) Completely rough bed } (k_s^+ > 70)\text{, where } k_s^+ = k_s/(v/U_*)\end{array}\right\} \quad (1)$$

Where **v** is the kinematic viscosity and U_* is the shear velocity. Roughness effects disappear if the bed is hydraulically smooth because of the viscous sublayer, whereas viscous effects appear in the case of completely rough beds because the roughness elements penetrate the fully turbulent logarithmic layer. An incompletely rough bed in the transition between a) and c), and it is affected by both viscosity and roughness.

As to question (2), no definite standard is available as yet. The theoretical wall level can be at a δ-position, below the top of the roughness elements, as shown in Figure (1).

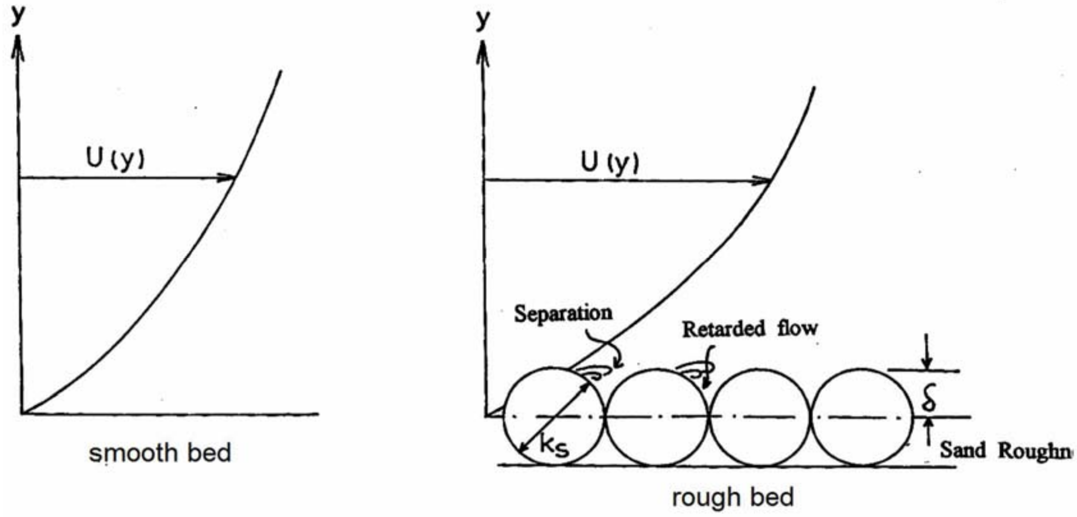

Figure 1: Schematic descriptions of turbulent flow over smooth and rough beds.

In physical applications, the value of δ should be at an intermediate point in the range $0 < \delta < k_s$. The value of δ can be determined so that the mean velocity distribution fits the log-law. The experimental data pertaining to δ/k_s leads to slightly different results depending on the researchers; see Table (1). Therefore the range of δ/k_s is about 0.18-0.70. Kirkgoz (1989) gave

$R_{e_*} = \frac{U_* h}{v}$ Where R_e: Reynolds number; h : water depth

$$\frac{\delta}{U_*} = 3.5 k_s^{+0.48} \quad (2)$$

$$\frac{\delta}{U_*} = 3.25 (k_s^+)^{-0.86} \quad (3)$$

Table 1: Values of δ/k_s

δ/k_s	Reference
0.18	Grass (1971)
0.27	Blinco and Partheniades (1971)
0.25	Nakagawa et al. (1975)
0.30	Kamphius (1974)
0.70	Bayazit (1976)
0.25	Song et al. (1994)

ROUGH BED MEAN VELOCITY

Measurements of velocity distribution over rough beds have been obtained by using pitot tubes (e.g., Reynolds 1974, and Coleman and Alonso 1983) and by using current flow meter, Ferro and Baiamonte (1994), and by using LDA (e.g., Kirkgoz 1989, Tominaga and Nezu 1992, and Song et al. 1994). The log-wake law of Equation over a smooth bed can be rearranged as follows:

$$U^+ = \frac{1}{\kappa}\ln(Y^+) + A_r + \omega(y/h) \tag{4}$$

Where $U^{+:}$ the shear velocity, κ: von Karman constant, A_r is the constant of integration, ω :

$$U^+ = \frac{1}{\kappa}\ln(y/k_s) + A_r + \omega(y/h) \tag{5}$$

$$A_r = \frac{1}{\kappa}\ln(K_s^+) + A \tag{6}$$

In the wall region, $y/h < 0.2$, the wake function can be neglected, Nezu and Nakagawa (1993), and Equation (5) coincides with the conventional log-law. Nikuradse's results for pipe flows reveal that A_r is a functional of k_s^+. In other words, although A_r obeys Equation (6) over a smooth bed, it deviates from Equation (6) and decreases gradually as k_s^+ increases. A_r is a constant equals to 8.5 for a completely rough wall, Nezu and Nakagawa (1993). Tominaga and Nezu (1992), Kirkgoz (1989), and Song et al. (1994); have proven that κ is also a universal constant irrespective of roughness size. Kirkgoz (1989) proposed a law-of-the-wall in the form

$$U^+ = 2.44\ln(Y^+) - 0.8 \tag{7}$$

With the range of Y^+ between 100 and 400. Song et al. (1994) adopted the Graf and Altinakar (1993) profile which reads:

$$U^+ = \frac{1}{\kappa}\ln\left(\frac{Y+Y_0}{k_s}\right) + A_r \tag{8}$$

Where $\kappa = 0.40$ is Karman's constant, $y_0 = 0.25k_s$ and A_r is the constant of integration which they found to be equal to 8.42 ± 0.22. They verified the validity of the log-law for the flow in steep open-channels.

In the outer region,$y/h > 0.2$, the Coles' law of the wake in form of:

$$U^+ = \frac{1}{\kappa}\ln\left(\frac{Y+Y_0}{k_s}\right) + A_r + \frac{2\Pi}{\kappa}sin^2\left(\frac{\pi(y+y_0)}{2(\Delta+y_0)}\right) \tag{9}$$

was given by Song et al. (1994), where Δ=boundary layer thickness. The π is the Cole's wake strength parameter its value accounts for the deviation for the law of the wall with large variation, 0.01< π < 0.15 with an average value, π = 0.08.

Ferro and Baiamonte (1994) used the following profiles to represent the mean velocity distribution through the entire depth of flow for rough bed channel flow, that is:

$$U^+ = b_0 + b_1 \log(y/h) + b_2 \log(y/h)^2 \left(1 - \frac{y}{h}\right) + b_3 (y/h)^2 \left(3 - 2\frac{y}{h}\right) \qquad (10)$$

In which b_0, b_1, b_2 and $b_3$are numerical constants to be estimated using velocity measurements. The $\Pi - value$ is not significantly different from zero for each bed shape they tested.

Coleman and Alonso (1983) gave a multiple-zone model, Equation (11), of velocity distribution throughout the complete inner and outer regions of smooth and rough open channel flows provided that $k_s^+ < 2000$

$$U^+ = \int_0^{y^+} \frac{2}{1 + \left\{1 + [2\kappa(t^+ + \Delta t^+]^2 \left[1 - exp\left(\frac{-t^+ - \Delta t^+}{26}\right)\right]^2\right\}^{1/2}} dt^+ + \left(\frac{y^+}{\Delta^+}\right)\left(1 - \frac{y^+}{\Delta^+}\right) + \left(\frac{2\Pi}{\kappa}\right)\left(\frac{y^+}{\Delta^+}\right)^2 \left[3 - 2\left(\frac{y^+}{\Delta^+}\right)\right] \qquad (11)$$

Where t^+ is a dummy variable and $\Delta^+ = \frac{\Delta U_*}{\nu}$ =dimensionless boundary layer thickness $\cong h$. If a standard value of κ, such as 0.41, is used, the model requires independent prediction of the parameters Δ^+,k_s^+, and Π in order to have practical use.

$$\Delta t^+ = 0.9\left[(k_s^+)^{1/2} - k_s^+ exp\left(\frac{-k_s^+}{6}\right)\right] \qquad (12)$$

EXPERIMENTAL SETUP AND PROCEDURE

The experiments were performed in a 5.5 m long, 0.25X0.25 m glass walled flume with an adjustable bed slope Figure (2). Velocity components were measured by the Laser-Doppler Anemometry (LDA) system.

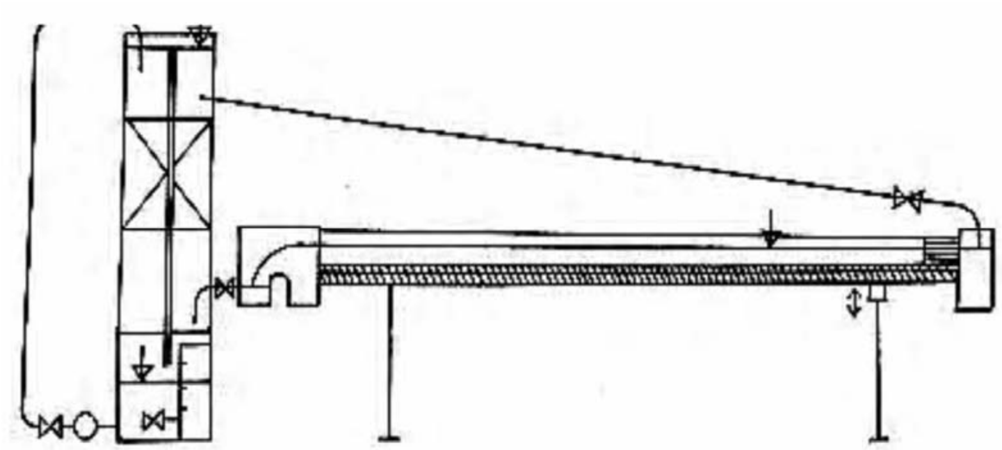

Figure 2: Experiment Setup

Three kinds of material were used in the rough-surface experiments.

a) Rough 1 – glass beads with uniform size of 5 mm in diameter and bed thickness in one layer of these beads (runs A1, B1 and C1)
b) Rough 2 – sand particles of diameter 4-8 mm and bed thickness is 15 mm (runs A2, B2 and C2)
c) Rough 3 – a layer of 20 mm in thickness made of gravel particles 10-25 mm in diameter (runs A3, B3 and C3)

The channel bed slopes varied from 0 to 0.00615 and the Froude number ranges between 0.167 and 1.310. Two flow regimes; the normal (uniform) flow regime for which the flow surface draws down in the downstream direction, and the backwater flow regime where the flow was kept horizontal by some kind of weir located at the outlet end of the flume.

For all tests water at room temperature was the fluid medium and the flow was kept steady and uniform. Flow velocities were measured at the mid span of measuring section. Some details are summarized in Table (2), in which q is the unit discharge of flow; h is the flow depth; R_h is the hydraulic radius of the flow cross-section; Um is the bulk mean velocity of flow; b/h is the flow aspect ratio; $Fr = \left(\frac{U_m}{\sqrt{gh}}\right)$ is the Froude number, $R_{eh} = U_m R_h / \nu$ is the Reynolds number based on the hydraulic radius; $U_*^{(1)}$ is the shear velocity calculated from the energy grade line, $U_* = \sqrt{gR_hS}$; $U_*^{(2)}$ is the friction velocity from the measured Reynolds-stress profile; $U_*^{(3)}$ is the shear velocity determined from the log-distribution

Table 2: Summary of the flow parameters for the study experiments

Flow Reg. (1)	Bed Type (2)	Run No. (3)	Channel Bed Slope (4)	q (l/s/m) (5)	h (mm) (6)	R_h (m) (7)	U_m (m/s) (8)	b/h (9)	Fr (10)	Re_h (11)	$U_*^{(1)}$ (cm/s) (12)	$U_*^{(2)}$ (cm/s) (13)	$U_*^{(3)}$ (cm/s) (14)	$U_*^{(4)}$ (cm/s) (15)	Π (17)
	Smooth	N1			40.00	0.030	0.405	6.25	0.65	49100	2.18	2.20	2.19		0.30
	Rough 1	A1	0.00123		42.50	0.032	0.381	5.88	0.59	48300	2.70	2.80			0.30
	Rough 2	A2			43.00	0.032	0.377	5.81	0.58	48250	3.28	3.20			0.30
	Rough 3	A3			48.00	0.035	0.338	5.21	0.49	46900	3.67	3.70			0.10
	Smooth	N2			25.00	0.021	0.648	10.00	1.31	53900	3.75	3.50	3.45		0.30
	Rough 1	B1		16.20	31.40	0.025	0.516	7.96	0.93	51800	4.20	4.00			0.10
	Rough 2	B2			36.20	0.028	0.448	6.91	0.75	50350	4.40	4.10			0.10
	Rough 3	B3	0.00615		39.80	0.030	0.407	6.28	0.65	49200	4.60	4.45			0.10
	Smooth	BW1			76.00	0.047	0.213	3.29	0.25	40300		1.10	1.16		0.55
	Rough 1	C1			70.00	0.045	0.231	3.57	0.28	41500		1.70			0.40
	Rough 2	C2			65.00	0.043	0.249	3.85	0.31	42600		2.15			0.30
	Rough 3	C3			60.50	0.041	0.268	4.13	0.35	43950		2.95			0.10
		N3		19.10	42.50	0.032	0.449	5.88	0.81	57520				2.25	
		N4		5.65	23.50	0.020	0.240	10.64	0.55	19234				1.45	
		N5		2.70	15.50	0.014	0.174	16.13	0.47	9608				1.13	
		BW2		19.04	110.00	0.059	0.173	2.27	0.23	40447				0.90	
	Smooth	BW3	0.0000	19.10	91.00	0.053	0.210	2.75	0.41	44520				1.05	
		BW4		19.10	74.50	0.047	0.258	3.36	0.38	48193				1.28	
		BW5		19.10	97.60	0.055	0.196	2.56	0.27	42902				0.97	
		BW6		19.10	69.30	0.045	0.276	3.61	0.42	49151				1.38	
		BW7		19.10	51.00	0.036	0.375	4.90	0.63	55346				1.79	

$$U^+ = \frac{1}{K}\ln(y^+) + A \quad (13)$$

With k=0.40 and A = 5.5; $U_*^{(4)}$ is the shear velocity determined to fit linear velocity distribution in the vicinity of the smooth (viscous sublayer).

$$U^+ = Y^+ \quad (14)$$

As well as the log-of-the-wall distribution, Equation (11) after Coleman and Alonso (1983); $U_*^{(5)}$ is the shear velocity estimated from the Vedula binary law (Vedula et al. 1985), and Π is Coles' wake strength parameter. For the first twelve runs measurements of mean and turbulence characteristics in x and y-direction are taken, while for the rest of the runs, only horizontal (longitudinal) components of mean point velocities are measured.

RESULTS AND DISCUSSION

Experiments data show that for any turbulent flow conditions, the mean velocity distribution requires a reasonable estimate of the shear velocity as close to the bed as possible, which can be obtained from the measured Reynolds, stress distribution. Figure (3) gives the non-dimensional measured velocity distribution for rough bed (rough 3).

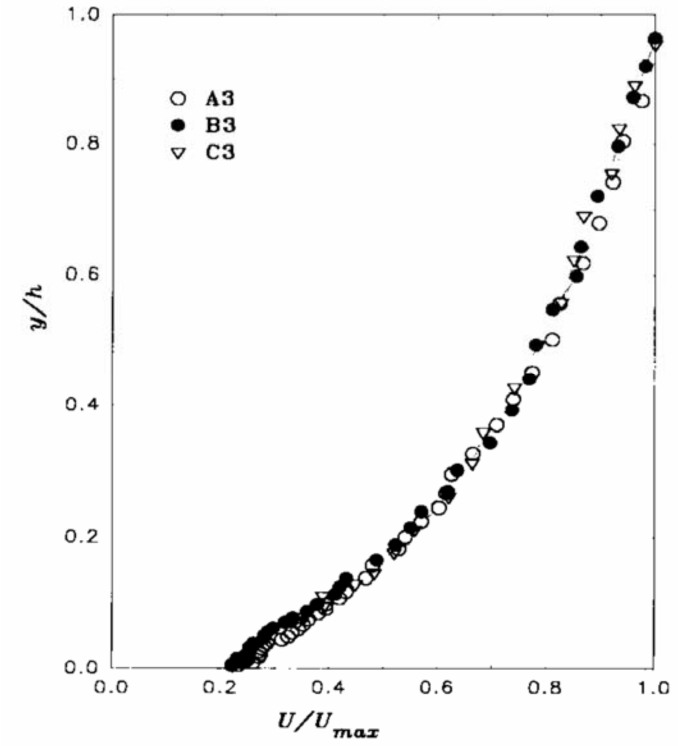

Figure 3: Non-dimensional velocity distribution for rough bed (rough 3)

DETERMINATION OF SHEAR VELOCITY

In previous investigations of rough surface velocity measurements, the determination of the reference level when the mean velocity is zero along the wall has been of considerable concern. The actual point where the velocity is zero remains below a certain proportion of the roughness elements, Figure (1). Several investigators have experimentally found values for δ varying between 0.18 k_s, and 0.7 k_s, Table (1). They assumed that the reference level shifts by an amount δ from the top of the average roughness level, k_s, making the water depth, in effect, $h+\delta$, and the fictitious flow through the depth, δ, is in laminar condition and can be obtained by extending the velocity profiles below the lowest velocity reading ΔU to intercept the $U=0$ line. With known values of ΔU and δ, shear velocity can be calculated using Equation (14). This approach is quite difficult for the following reasons:

- The roughness elements are not uniform and are not always in one layer which makes the definition of k_s itself doubtful.
- Even for LDA measurement it is very hard to measure the mean velocity very near to the bed roughness elements, leading to very few points being detectable, and any

extension of these points is very variable resulting in different values of shear velocity.

- Figure (4) shows that the flow velocity in the vicinity of the wall has approximately constant values, so using Equation (14) is practically impossible.

In this study the shear velocities for rough beds have been obtained from the measured Reynolds stress distribution and by using a binary law of velocity distribution presented by Vedula et al. (1985). The shear velocity increases with increasing Reynolds number for the same type of roughness, Table (2). Figure (5) contains the measured velocity distributions.

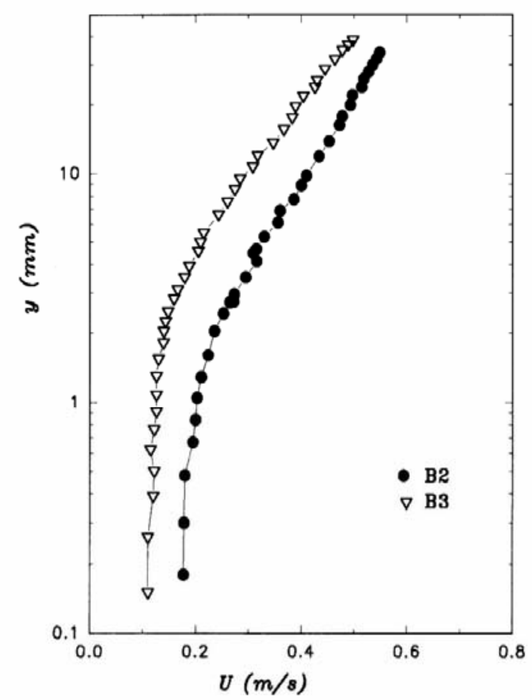

Figure 4: Measured velocity distributions near rough beds

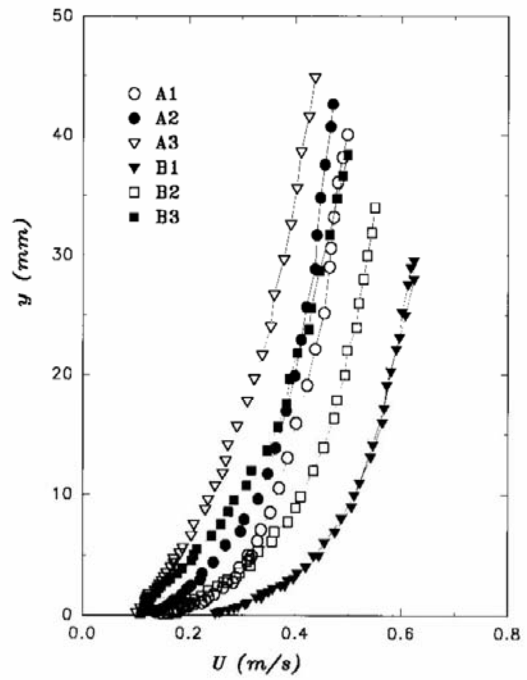

Figure 5: Measured velocity distributions for rough beds with normal flow regime

LAW-OF-THE-WALL DISTRIBUTION

The mean velocities on the rough beds are fitted to the law-of-the-wall distribution in different ways depending on shear velocity values and some theoretical models. Figure (6) presents the distribution for a rough bed compared with the theoretical model (Equation 11). With κ = 0.410 and A= -0.8 as proposed by Kirkgoz (1989). The Shear velocities used in this comparison are estimated according to Vedula et al. (1985). The roughness type in this plot is glass beads (Rough 1). The distribution is quite different from that of a smooth bed. Compared to the smooth wall results, the values of U^+ are much lower for rough surfaces. As may be seen from the figure, the point where the law-of-the-wall distribution becomes applicable (with κ = 0.41 and A = -0.8) moves to higher values, about $y^+ = 100$, in comparison to the smooth wall case. In the fully turbulent part of the inner region (that is, between $y^+ = 100$ and 600) the data seem to follow the model reasonably well.

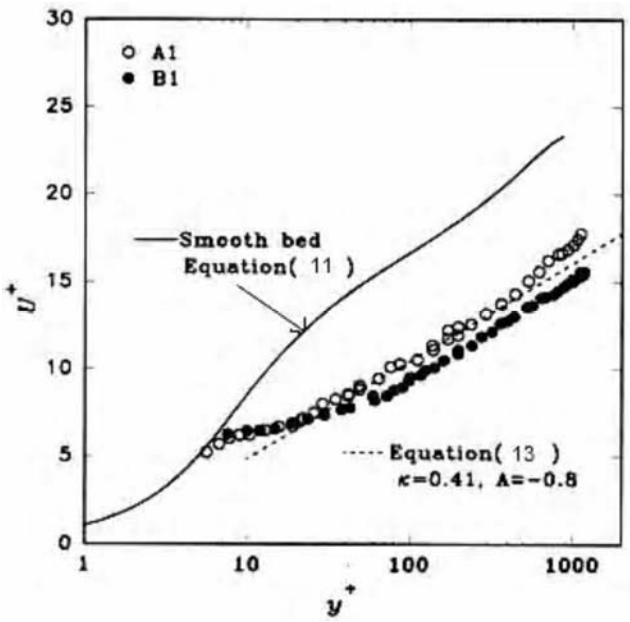

Figure 6: Law-of-the-wall distributions for rough bed with normal flow regime compared with the theoretical model (Equation 11)

The shear velocities determined from Reynolds shear stress distribution are used to present all the rough bed flow velocities in comparison with the theoretical model given by Coleman and Alonso (1983), Equation (11), which covers the whole range of flow regions. From Figure (7) and (8) it can be seen that the data from rough beds is scattered around the theoretical line of the model in the lower part of the curve and converge in the upper part of the model line.

The figures also show that the velocity profiles have the same trend in the same region of flow even though these plots are under varied conditions of flow but for the same roughness in each figure.

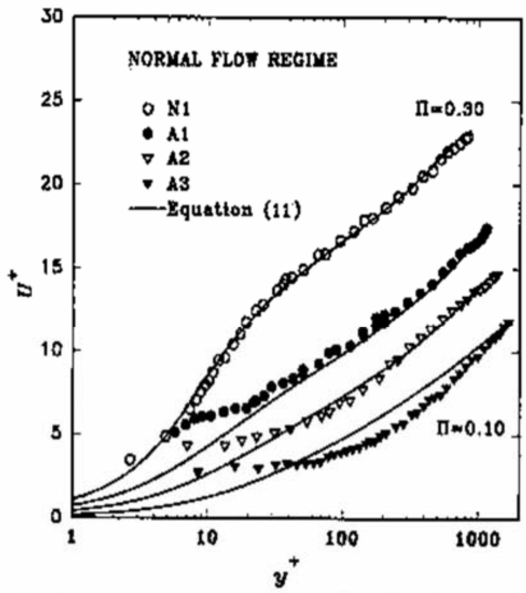

Figure 7: Law-of-the-wall distribution for rough beds with normal flow regime

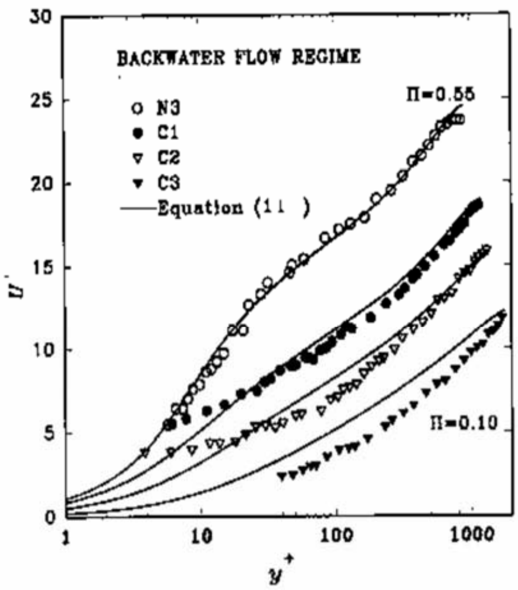

Figure 8: Law-of-the-wall distributions for rough beds with backwater flow regime

VELOCITY-DEFECT DISTRIBUTION

The velocity-defect distribution of the data for the three rough surfaces considered is shown in Figures (9) and (10). As may be seen from the figures the data are not so scattered and it might be possible to draw a single line to fit the data in the lower part of the curve that is when $y/h \geq 0.6$. Figure (10) shows the velocity-defect distribution for Rough 3. It shows that the constant velocity of flow in the vicinity of the bed, and the data points fall on the same line for the different flow conditions, refer to Table (2).

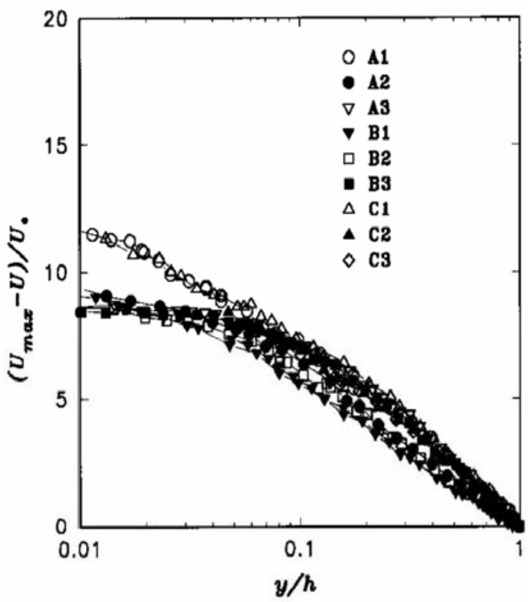

Figure 9: Velocity-defect distributions for rough beds

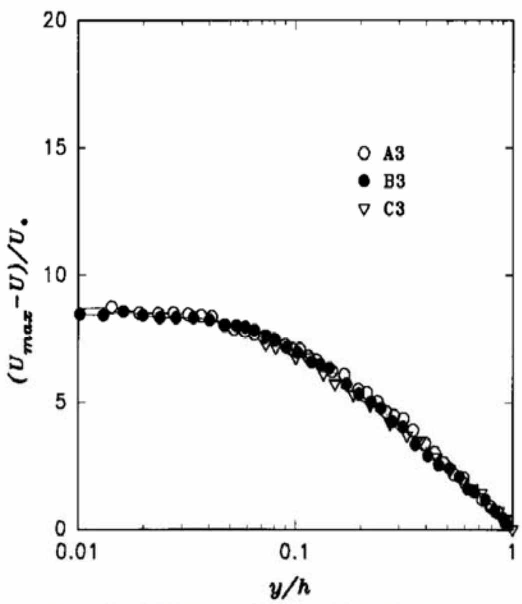

Figure 10: Velocity-defect distribution for Rough 3

For the range of the data tested and under the flow conditions considered, a conclusion can be drawn regarding the velocity profiles of the horizontal (longitudinal) components in the sense that the theoretical profile which was given by Coleman and Alonso (1983) can describe the velocity distribution through the whole depth of flow and for both smooth and rough beds with some prediction for the parameters $\Delta^+, k_s^+, and\ \Pi$.

TURBULENCE-INTENSITY DISTRIBUTIONS

For uniform open-channel flow, Nezu and Nakagawa (1993) suggested that the turbulence intensities are distributed according to an exponential law. Turbulence intensities for horizontal (longitudinal) velocity fluctuations for some experiments are plotted in Figure (11). There is the same tendency observed by Nezu and Nakagawa (1993) and others. Also given are the distributions calculated by Nezu and Rodi (1986) which read,

$$\frac{u}{U_*} = 2.26 \exp\left(-0.88\frac{y}{h}\right) \tag{15}$$

Here u stands for the root-mean-square (rms) value for the fluctuating exponents of the flow velocity. Although the present data is so scattered near the channel bed it shows a reasonable agreement with Equation (15) and the measured data fall within the experimental scatter. Turbulence intensities for vertical velocity fluctuations are plotted in Figure (12). There is an overall decrease of v with increasing depth, but within the inner region $(y/h \leq 0.2)$ a decreasing tendency is noticeable. Also given is the distribution calculated by Nezu and Rodi (1985), which reads

$$\frac{v}{U_*} = 1.23 \exp\left(-0.67 \frac{y}{h}\right) \tag{16}$$

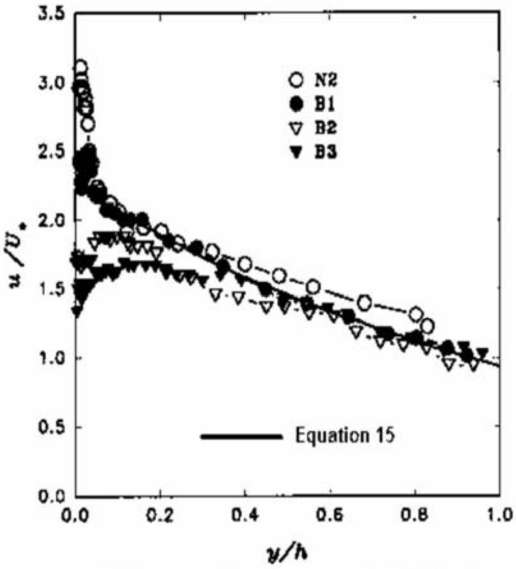

Figure 11: Turbulent intensity u/U_* in the outer region

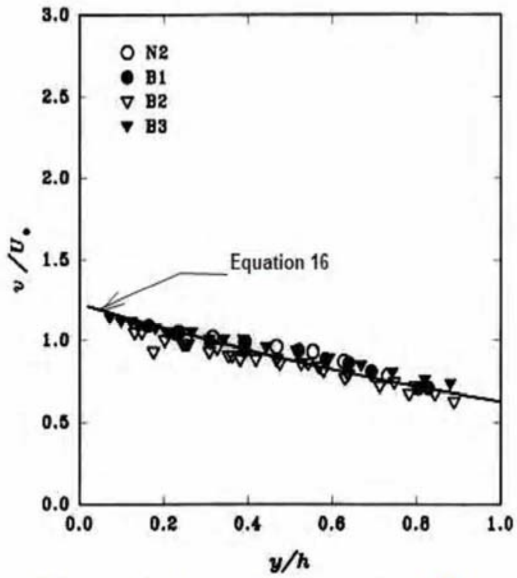

Figure 12: Turbulent intensity v/U_*

REYNOLDS-STRESS DISTRIBUTION

The total shear stress, τ, is well presented by the Reynolds stress over a large distance. If the Reynolds number id large the distribution is given by velocity.

$$\tau = -\rho uv = \rho U_*^2 \left(1 - \frac{y}{h}\right) \tag{17}$$

This is a linear relation valid for rough boundaries in turbulent flow. Reynolds stress profiles are presented in Figure (13). The experimental data was plotted to the theoretical distribution given by Equation (17) by estimating a value for the shear, U_*, to give the best fit.

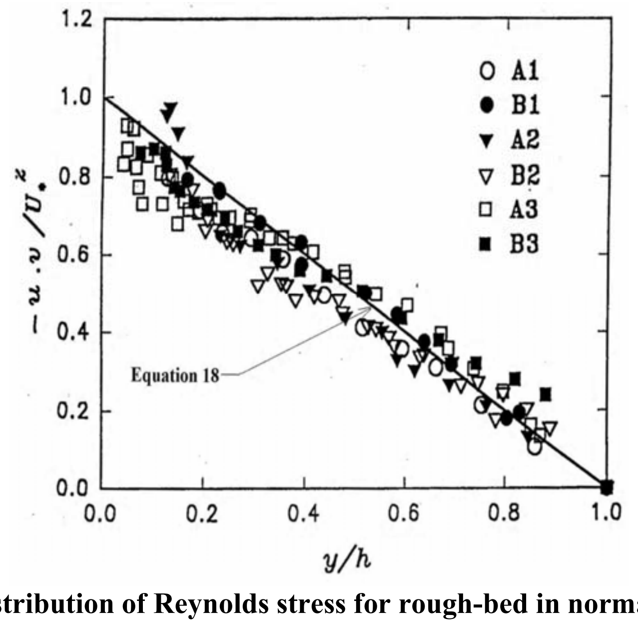

Figure 13: Distribution of Reynolds stress for rough-bed in normal flow regime

Despite some experiments scatter, the present data, Figure (13), shows a reasonable agreement with the linear distribution in the case normal flow regime and to a less extent for a backwater flow regime.

CONCLUSIONS

Flow velocities were measured by LDA at mid-vertical of the flow cross-section, where the flow is supposed to be two dimensional. From the presented data, it can be concluded that:

- For any turbulent flow conditions, determination of velocity distribution along the vertical requires an acceptable estimate of the shear velocity, which is not an independent parameter. It depends on other factors; hence it is quite valuable to determine the shear velocity as close as possible to the actual value in order to be able to have a reasonable close distribution to the real case.
- Although von Karman constant, κ, and the constant of integration, A, may have some kind of universal value, it remains well known that each case of flow has its own conditions and properties and it has to be treated within the frame of the dependant parameters and their specific cases. Velocity profiles are extremely sensitive to the κ values and to a less extent to the A constant value.
- Shear velocity of flow can be reasonably estimated from the measured Reynolds stress distribution.
- The data from rough beds are scattered around the theoretical line of Coleman and Alonso (1983) model in the lower part and converges in the upper part of the curve. These velocity profiles have the same trend in the same region with different conditions of flow but for the same roughness.
- The turbulence intensity distribution shows a reasonable agreement with distribution calculated by Nezu and Rodi (1985).
- The Reynolds-stress distribution is a linear relation.

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